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Research on the recycling methods for lithium-ion batteries in the electric vehicle industry

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Abstract. The accelerating threat of climate change has spotlighted the imperative for greener transportation solutions, resulting in the swift transition to electric vehicles (EVs). An essential aspect of this transformation is the integration of lithium-ion batteries as energy storage. However, the subsequent challenge of managing end-of-life batteries has underscored the urgency for efficient recycling strategies to mitigate environmental risks and economic losses. By researching current valuable articles, this article gives an overview of the current challenges in recycling lithium-ion batteries, including issues with electrode materials, ageing, and safety concerns, as well as various recycling techniques explored in response to these challenges, such as pyrometallurgical and hydrometallurgical processes, direct recycling, and emerging biological recycling methods.

Keywords: lithium-ion battery recycling, electric vehicle industry, battery waste management, recycling techniques.

1. Introduction

Carbon emissions from transportation have a severe impact on the climate. One of many solutions for the modern automobile industry is converting its production from fuel to electric vehicles. Lithium-ion batteries are the most common solution for energy storage in the electric vehicle industry. However, abandoned battery packs could be a tough challenge to handle. The unappropriated disposal of the waste batteries may cause potential danger and economic loss. Thus, the standard and scaled procedure for recycling various types of batteries shall be carried out. This article aims to provide an overview of current recycling techniques and potential new methods by reviewing papers in this field. This article will focus on methods of battery disassembly and multiple ways to recover Li-ion material and other metal components in the battery. With detailed explanations, this review may help researchers in related fields to discover the drawbacks of existing recycling methods and the possibility that they will uncover more effective ways to recycle lithium-ion batteries.

2. Fundamental concepts about electric vehicles and Li-ion batteries

2.1. How E.V. works

To illustrate the importance of recycling batteries, a fundamental principle of how electric vehicles and Lithium-ion batteries works should be explained. As Figure 1 shows, a standard E.V. contains four main

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parts: Battery packs to provide energy, a Power converter to convert electrical power, an Electric motor to convert electric energy to kinetic energy, and Mechanical transmission to transfer power output from the motor to the wheels [1].

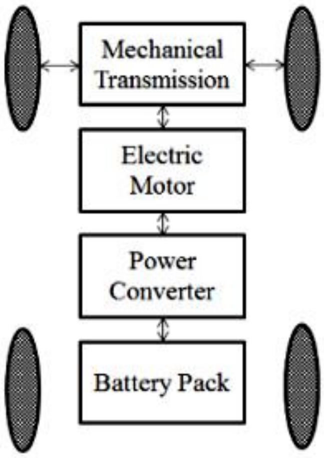

Figure 1. Layout of E.V [2].

2.2. Why Li-ions battery is used

To ensure the convenience and economic efficiency of E.V.s, the battery shall be light in its weight and could last for a long time of power output once fully charged. This leads to a high energy density per Liter and Kg, meaning this material has the same amount of electric energy but is smaller and lighter in its weight. In Figure 2, as the material lies in the up-right corner, it fits more on the needs mentioned before. However, Li metal batteries were considered unsafe for several reasons: When rapidly charged and discharged, dendrites might be formed on the surface of the Lithium anode. Which could grow with time and finally damage the separator in the battery and cause a short circuit. Li-metal batteries can be overcharged during the charging process, leading to surface Li on the anode being deposed and a rise in the chance of short circuits. Li metal is highly reactive; heat and gas are released when it goes through an uncontrolled reaction. This results in the potential risk of explosion [3]. Thus, safer and relatively efficient Li-ion batteries are widely used in the E.V. industry.

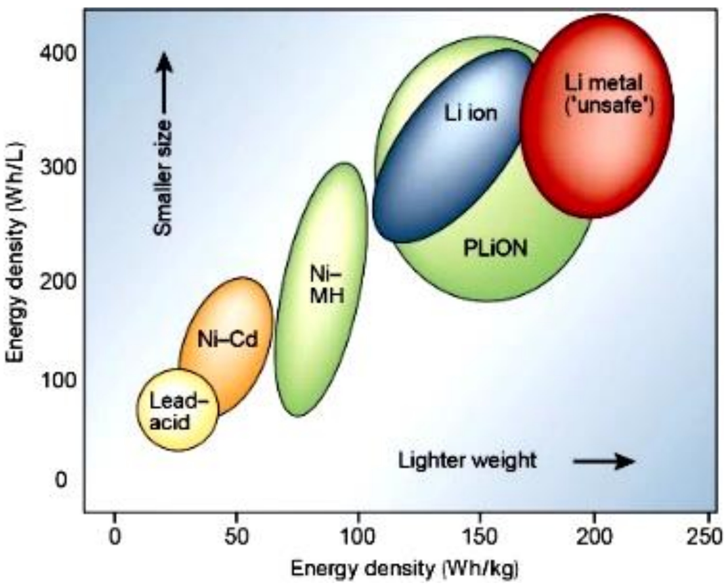

Figure 2. Energy density diagram [4].

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2.3. How Li-ion battery works

Chemical cells work on a basic principle: The movements of ions transfer charges between two electrodes. In the case of a Li-ion battery, lithium ions are transferred between the anode and cathode [5]. During charging, lithium ions are extracted from the cathode, moved through the electrolyte, and stored in the cathode. Lithium ions move back to the cathode and release electric energy when a complete circuit is connected to the battery.

2.4. Main components

Anodes are mostly made of graphite, which is responsible for storing LI ions during charging. Cathodes are usually made of lithium metal oxide; lithium cobalt oxide ($LiCoO_2$) and lithium iron phosphate ($LiFePO_4$) are widely used.

A typical electrolyte in Li-ion batteries is lithium salt dissolves in organic solutions (Ethylene Carbonate, Diethyl Carbonate, and Dimethyl Carbonate are common examples).

Separators are leachy materials between the anode and cathode, allowing electrolytes to pass without direct contact with the anode and cathode [6].

3. Methods of recycling Li-ion battery

Based on 'Key Challenges and Opportunities for Recycling Electric Vehicle Battery Materials' by Beaudet, Alexandre etc., it is claimed in this paper that battery recycling is facing economic, technical, environmental, political and market challenges [7]. This paper will focus on the technical challenges this technic is encountering.

As mentioned earlier, anodes are typically made with graphite. This material is relatively inert and could be easily extracted from the battery. However, with an extended use time, its structure may change, and it is not easy to reform its original structure [8].

With the use of a battery, there would be substances deposition on the cathode and anode, loss of cyclable Li-ion, and the cracking of electrodes due to the fast charging causing uneven distribution of Li [9, 10].

Inappropriate methods of dealing with wasted Li-ion batteries are dangerous, fire hazards could be caused by thermal runaways, and hazardous chemicals might be released as well [11].

3.1. Pyrometallurgical recycling

'Pyrometallurgical recycling of Li-ion, Ni–Cd and Ni–M.H. batteries: A minireview' by Mohammad Assefi, Samane Maroufi, Yusuke Yamauchi, Veena Sahajwalla reviewed the pyrometallurgical method of recycling metals in the battery, a thermal process for recycling Li-ion batteries was discussed in this article. This process involves high temperatures to recover high-value metals from batteries. In this method, batteries undergo thermal treatment with a typical temperature between 400°C and 800°C, reducing agents reacted with battery material, causing the reduction of metal oxide. Reduced metals form alloys or diffuse into a metallic phase. Lithium-containing substances would be captured by slag, which may also contain impurities. Further separation is carried out using 'post-treatment leaching processes. This step is to separate and purify recovered metals [12]. Note that the specific conditions and parameters of the thermal process may vary depending on the battery composition and desired metal recovery. Meanwhile, this method has its limitations. It includes a high-temperature process; the energy cost of this process is high and relatively inefficient [13]. These drawbacks of pyrometallurgical recycling lead to a more efficient and lower-cost process: the hydrometallurgical process.

3.2. Hydrometallurgical process

In 'A brief review on hydrometallurgical technologies for recycling spent lithium-ion batteries' by Alexandre Chagnes and Beata Pospiech. A more efficient method with superior extraction effectiveness, reduced energy consumption, and minimal emission of harmful gases is discussed. The hydrometallurgical process is commonly used for the recycling of wasted Li-ion batteries. This process involves several steps: pretreatment, leaching, purification, and recovering valuable metals. Firstly, the battery would be sorted and physically processed to separate the electrodes from other components. Then metals would be extracted from the electrode using leaching reagents (acid is the most common leaching reagent). After leaching, the purification stage involves separating the extracted metals from impurities. This can be done through solvent extraction, precipitation, or other purification techniques [14]. The recovered metals could be further processed, such as further purification, to achieve higher purity.

3.3. Direct recycling

Direct recycling is defined as the recovery, regeneration, and reuse of components in a battery with no transformation of its original chemical structure; in this process, batteries are discharged, disassembled, and ripped and await further processing [15]. A newly developed relevant technology: Cathode-healing™, has drawn attention from many studies; it aims to restore the performance and structure of the aged cathode material in Li-ion batteries. In 'A direct recycling case study from a lithium-ion battery recall' by Steve Sloop, Lauren Crandon and Marshall Allen, this technology is introduced in steps. It involves a hydrothermal treatment process where the cathode material undergoes high temperature and pressure conditions with a lithium-rich aqueous solution; this method also involves rinsing the treated cathode with purified water to remove any residual lithium solution [16]. It was claimed to be a low-cost and feasible method, and it could 'fully recover end-of-life NCM 622(Lithium Nickel Cobalt Manganese Oxide; a kind of cathode material)' [17].

Solvent Recovery of Electrode Materials is another process under this category. Based on ‘Sustainable Direct Recycling of Lithium-Ion Batteries via Solvent Recovery of Electrode Materials’ by Yaocai Bai, Nitin Muralidharan, and Jianlin Li, it refers to a process in which solvent is used to separate the electrode materials from aluminium foils in spent lithium-ion batteries. The process involves placing the electrodes in a heated solvent, which causes the cathode materials to delaminate from the aluminium foils. The delaminated cathode materials and aluminium foils are then separated from the solvent for further use [18]. This solvent-based separation process is non-destructive to the morphology and crystal structure of the electrode materials, making it suitable for direct recycling and regeneration of cathode materials for new battery manufacturing [19].

3.4. Biological recycling

Biological recycling refers to using biological processes and organisms to recover and recycle valuable elements from waste products. It involves harnessing the metabolic activities of microorganisms or biomolecules to transform, extract, or adsorb metals or other valuable components from various waste sources, such as technical products, industrial wastewater, or processing wastes [20]. Biological approaches for recycling can include bioleaching, biomineralization, bioremediation, and bioaccumulation, among others [21]. This process can be used as a tool for clean industrial processes, recovery of metals, production of bio-based materials, and green recycling processes. Biological recycling offers a sustainable and environmentally friendly alternative to traditional recycling methods by utilizing natural processes and reducing the need for toxic chemicals and energy-intensive processes. Despite the promising outlook for this technology, little research has been done in this field; no stable large-scale process has been invented.

4. Conclusion

Based on the current technological challenges of recycling Li-ion batteries, various methods have been provided. Each method offers different advantages and drawbacks, and ongoing research in this area is crucial for developing more efficient and environmentally friendly approaches. As the author considers, Biological recycling provides the most promising outlook for recycling technology. However, during the research, this article failed to find papers relating to the application of this method. Hopefully, further study on this method will be carried out. The success in recycling lithium-ion batteries is not only an environmental responsibility but also a significant economic opportunity. Embracing recycling technologies and promoting circular economy principles will provide a cleaner and more sustainable future where electric vehicles can truly fulfill their potential as a transformative force in combating climate change and reducing carbon emissions.

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